The opposition of Mars, 2020: Part I

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A report of the Mars Section. Director: R. J. McKim

For UK observers, 2020 was the most favourable year of the 15- or 17-year opposition cycle. An extremely comprehensive set of some 11,600 observations was obtained by 147 observers. In Part I we discuss the impact of dust storms upon albedo features and deduce velocities for the initial expansion of one such storm. Several striking albedo changes were found to have persisted since 2018–'19: in particular, the development of *Indus* between *Oxia Palus* and *Mare Acidalium*, and the canal-like *Phasis* west of *Solis Lacus*. The slow fading of several northern-hemisphere markings such as the *Aetheria* development, *Trivium Charontis – Cerberus* and *Nodus Alcyonius* continued. The opposition period saw clear Martian skies, but before and after closest approach, two large regional dust storms were observed, both of which commenced in S. *Chryse – Xanthe / Valles Marineris*, and stretched from *Hellas* in the east to *Daedalia* in the west. This initiation site has been the favoured one for some years now, whereas in the past many such events originated in NW *Hellas* and spread as far west as *Argyre*. Lists of both types of storms are presented in an appendix. A second appendix deals with the measurement of cloud velocities. In Part II, the behaviour of white clouds and the polar regions will be discussed.

Introduction

Mars was at opposition on 2020 Oct 13 (disc diameter (D) = 22.3 arcseconds, ″), with closest approach on Oct 6 (D = 22.6″). The sub-Earth latitude (D_e) at opposition was +5.5°, and D equalled 6″ or greater from 2020 Mar 19 till 2021 Mar 10. The 2020 perihelic opposition was the most favourable for UK observers in the 15- or 17-year cycle, as with seasonally comparable oppositions in the Section's history: 1894,[1] 1909,[2] 1926,[3] 1941,[4] 1958,[5] 1973,[6] 1988,[7] and 2005.[8] Seasonal and other dates are listed in Table 1.

Observations covered the period from 2019 Oct 31 (drawing by D. Gray, at areocentric longitude Ls = 100°; the first image was by C. Foster, Nov 7) to 2021 Jul 29 (image by A. S. Kidd, Ls = 79°; last drawing was by R. J. McKim, Jun 5) from early northern summer in Martian Year (MY) 35 till late northern spring in MY 36: 94% of a 360° interval in Ls. An unbroken run of 435 consecutive days between 2020 Mar 2 and 2021 May 10 was achieved. In all, 537 dates were covered by 11,676 observations (9,908 images and 1,768 drawings) from 147 observers (Table 2). In the UK, high-resolution images were communicated by D. L. Arditti, P. Edwards, N. J. Haigh, A. S. Kidd, W. J. Leatherbarrow, M. R. Lewis, D. A. Peach (some in collaboration with E. Enzmann on La Palma, or *via* Chilescope) and D. B. V. Tyler, supported by many others. The Director obtained 220 drawings (see Figure 9 and Part II, Figure 11) and good totals were obtained by P. G. Abel and C. Nuttall. Of the overseas observers, H. Einaga, P. Gorczynski and M. Hood each secured over 250 observations, while M. Adachi, T. Arakawa, S. Ito, T. Kumamori, P. W. Maxson and K. Yunoki each made over 500. We regret the deaths of Peter Edwards and Ken Medway since the completion of this report.

The planet's declination (+5.5° at opposition) was only slightly north of the celestial equator for much of 2020, enabling our Australian friends also to experience Mars at a reasonable altitude. On an historical note, members of the Société Astronomique de France renovated the 216mm reflector once used by E-M. Antoniadi, a former Director (1896–1917) of our Mars Section. They took comparative images through it and the restored 250mm refractor of the Flammarion Observatory, Juvisy.[9]

The COVID-19 worldwide pandemic limited overseas travel and the direct use of many professional instruments. W. P. Sheehan was almost alone in being able to use the 600mm refractor of Lowell Observatory on a few nights, while Pellier was able to visit Saint-Véran Observatory. Severe and enduring as it was, the pandemic did not in any way limit the determination of observers.

The writer maintained a frequently updated opposition web page at the Section website.[10] This was updated daily throughout the large regional dust storm of 2020 November and was the Director's main method of communicating news. A few dust storm alerts were sent out by e-mail and posted upon the BAA Forum page. Several interim reports were prepared,[11–14] the first containing an opposition preview. The writer prepared a preview in his 'Sky Notes' for the cancelled BAA Ordinary Meeting in 2020 March, as well as a tutorial on planetary sketching.[15]

With air travel on Earth severely restricted, 2021 February was ironically a busy month for interplanetary exploration. On 2021 Feb 9, the UAE Space Agency *Hope* probe went into orbit,[16] followed the very next day by a spacecraft from China, *Tianwen-1*,[17] while on Feb 18 the NASA *Perseverance* rover landed at the 49km-diameter Jezero crater (+18°, 282°),[12,13,18] a feature possessing a fan-shaped delta and with clear evidence of flowing water in the geological past. Later, there were several flights by its little helicopter, and the first-ever successful extraction of oxygen from the Martian atmosphere.[13] The former two missions consisted of an orbiter, lander and rover. The UAE mission involved insertion into a highly elliptical orbit which at closest approach usefully corresponds to a geostationary one, and at its furthest

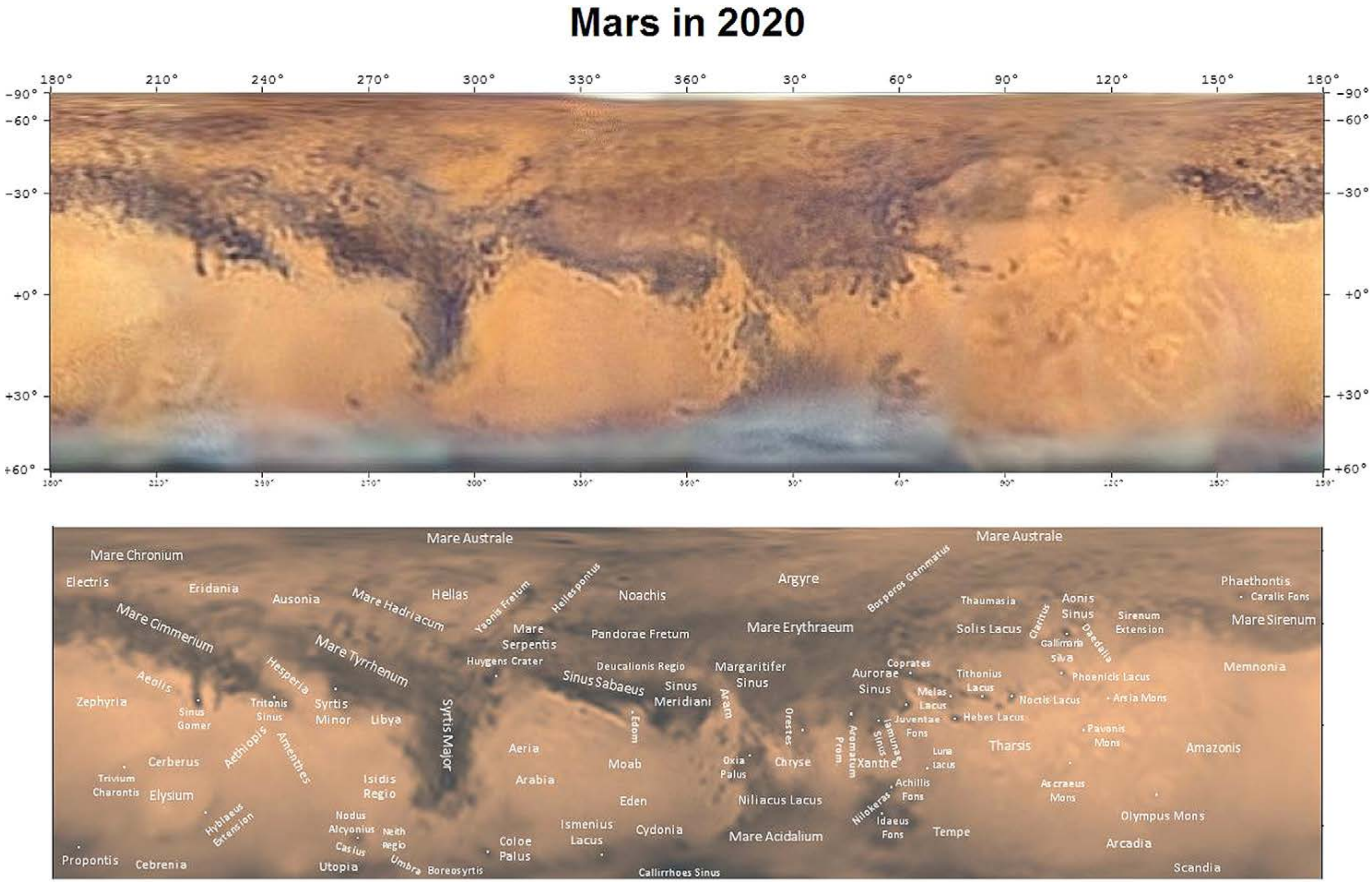

Figure 1. *Top*: Apparition map for 2020 by T. Kumamori, from his RGB images with a 355mm SCT and ASI 290MM & ASI 462MC cameras, Aug 15 – Oct 25. *Bottom*: 2020 map by M. R. Lewis from colourised λ = 642nm images with a 444mm refl. and ASI 174MM camera, September–November. Both maps have planetocentric latitudes and cylindrical projections. Since this report was completed, an even more detailed map has been constructed by Peach. *Note*: South is uppermost in all illustrations.

facilitates whole-planet imaging. A recent review summarises the type of meteorological data collected by present and past landers and rovers.[19]

The observations

Albedo features

We continue to use telescopic nomenclature.[20] Apparition maps by T. Kumamori and M. R. Lewis appear in Figure 1. Albedo changes due to the 2018 global storm have been discussed elsewhere.[12] Of the latter, the developments at *Phasis* and *Indus* were the most strikingly enduring. Here we record how the albedo markings responded to the further storms of 2020. Near opposition, the different colours of the markings were beautifully seen, and with large apertures the maria could be resolved into innumerable tiny spots, this being the experience of the Director rather frequently during September–October, whenever the seeing was very good. The present report continues from that for 2018.[21]

Region I: long. 250–010°

See Figures 1 & 2. The features at the NW corner of *Syrtis Major*, around Antoniadi crater, were rather conspicuous but not abnormal. This area had experienced an albedo anomaly at the time of the 2018 global storm. To the north-east, *Nodus Alcyonius* remained faint. *Hellespontus* was darkened and greatly broadened by the 2020 June–July large regional dust storm, while the large November regional event deposited a complex pattern of fallout over S. and SE *Iapigia*.

The location of the *Huygens* crater was well seen, marked by a large dark patch upon its floor. The best images showed remarkably complex details upon the latter albedo marking.

Moeris Lacus formed a small, elongated spot on the E. side of the *Syrtis*, but the *Nepenthes* streak (which commences there) remained largely invisible, as it has done for decades. Interestingly, a broad but extremely faint and diffuse shading was seen in its place when the phase angle was high (on the morning side) in 2021 March. Such lighting conditions can sometimes exaggerate the contrast of certain halftone albedo markings, as observed with several other features in the past, but the Director has not previously noticed it with *Nepenthes*. Its appearance upon the images by Kurisu on Mar 23 and Enzmann & Peach on Mar 31 recall, albeit in a very much fainter form, its form around 1958 or 1960. A similar effect is apparent upon some 2020 February–April images, when there was an equally strong phase effect upon the evening side, while the Director had an incomplete visual impression in early 2020 November, due to diffuse and curved shadings E. of *Isidis Regio*. Will *Nepenthes* return one day?

Pandorae Fretum was essentially invisible in the early part of the apparition (though *Noachis* on its S. border was rather dark

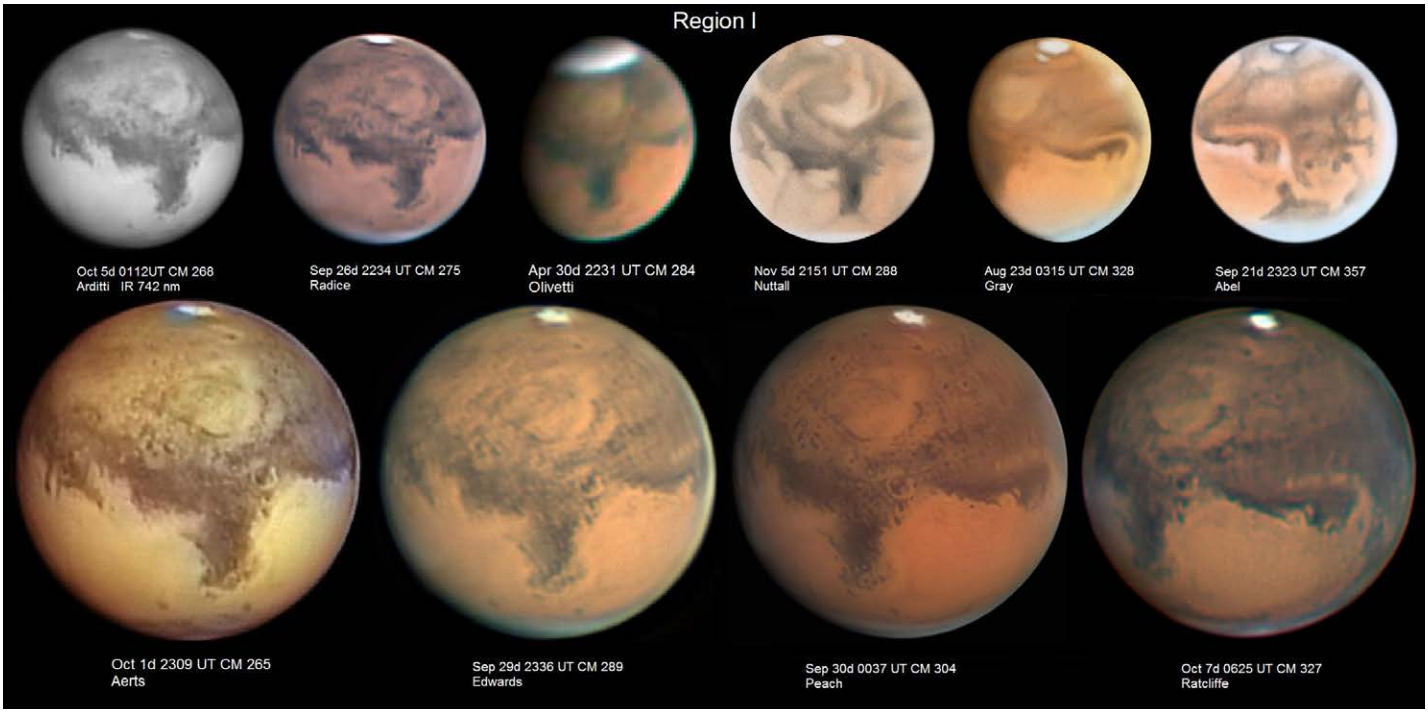

Figure 2. ***Region I.*** Images (RGB except where stated) and drawings in 2020, by P. G. Abel (305mm refl., ×375), L. Aerts (ASI 178MM camera), D. L. Arditti (Flea 3), P. Edwards (ASI 224MC), D. Gray (×385), C. Nuttall (×410), T. Olivetti (PG GS3 IMX252), D. A. Peach (355mm SCT and ASI 290MM), M. Radice (ASI 224MC) and M. Ratcliffe (ASI 290MM).

during the first half of 2020, and much darker than *Deucalionis Regio*), continuing to be so until after the large regional storm of June–July. As soon as the latter had subsided, by mid-July, *Pandorae* was seen to have become broad and dark, remaining thus for the rest of the apparition. The June–July storm darkened the E. half of *Deucalionis Regio*. The latter change persisted for the remainder of 2020–'21, being missed by several visual observers, but it was shown clearly by Giuntoli with a 100mm OG.

Region II: long. 010–130°

See Figures 1, 3 & 5. The great development at *Indus* (connected to SE *Mare Acidalium*), which had been a result of the 2018 global storm, survived the 2019 January regional event.[21] About 2020 Feb 21, there was a short-lived local dust storm over W. *Deucalionis Regio* (see later), and a few days afterward an image by Peach on Feb 26 showed the configuration again changed, due to fallout from that event. Now the N*p*. (*p.* = preceding) part of *Margaritifer Sinus* had faded, and *Hydaspis* to the west was again extended and darkened, giving the area an even more peculiar appearance. However, *Margaritifer* and its connection with *Oxia Palus* slowly darkened while *Hydaspis* faded slightly, doubtless owing to a small regional storm in April (see later), so that by late that month the area looked more normal, though the darkened and broadened *Indus* persisted throughout. The latter development was still clearly visible as late as 2021 July. In Figure 5, we show the sequence of changes since 1999.

Solis Lacus and the *Phasis* development remained prominent. *Tithonius Lacus* was not as dark as it sometimes is, suggesting that post-global storm fallout in the canyons of *Valles Marineris* had raised its albedo.

The orographic clouds over the *Tharsis Montes* (as well as *Olympus Mons*) are detailed in Part II. With the Martian atmosphere clear and transparent, it was possible to see – especially a fortnight or so either side of opposition – the 'opposition effect' upon the slopes of the Martian volcanoes, when they brighten considerably. All these volcanoes, as well as *Elysium Mons* and *Hecates Tholus*, showed it.

Region III: long. 130–250°

See Figures 1 & 4. Dust fallout that had affected *Nodus Alcyonius* in 2018 also caused a further fading of the long-enduring *Aetheria* development, while *Cerberus* and *Trivium Charontis* remained very faint. A long way from opposition, in 2020 May, the faint *Cerberus* had appeared a little darker (relatively), but this was merely a further example of the phase effect. In the south,

Table 1. Physical details of the 2020 apparition

	Ls (°)	*Date*
Solar conjunction	74	2019 Sep 2
N. summer solstice/ S. winter solstice	90	2019 Oct 8
N. autumn equinox/ S. spring equinox	180	2020 Apr 8
Perihelion	250	2020 Aug 2
N. winter solstice/ S. summer solstice	270	2020 Sep 2
Closest approach	291	2020 Oct 6
Opposition	295	2020 Oct 13
N. spring equinox/ S. autumn equinox (MY 36 commences)	0	2021 Feb 7
Aphelion	70	2021 Jul 10
N. summer solstice/ S. winter solstice	90	2021 Aug 25
Solar conjunction	110	2021 Oct 8

These data are taken from *The Astronomical Ephemeris* published jointly by HMNAO & the US Naval Observatory, and are currently generated from the JPL DE405 planetary and lunar ephemerides. During 1986–2018, we largely used data from this source, then conveniently serialised by the Oriental Astronomical Association in its *Communications in Mars Observations* bulletins. Some tiny differences exist between this programme and *WinJUPOS.*

Table 2. Observers of Mars, 2020

Name	*Location*	*Instrument(s)*
P. G. Abel **V**	Leicester	203mm & 305mm refls.
M. Adachi **V**	Otsu, Japan	355mm refl.
	Dynic Obsy., Shiga, Japan	600mm Cass.
G. Adamoli **V**	Verona, Italy	125mm MKT & 235mm SCT
L. Aerts	Heist-op-den Berg, Belgium	250mm & 355mm SCT
T. Akutsu	Ibaraki, Japan	450mm refl.
T. Arakawa	Nara, Japan	400mm DK Cass.
M. Araújo	Évora, Portugal	279mm SCT
D. L. Arditti	Edgware, Middlesex	355mm SCT
K. N. L. Bailey	Wroughton, Wilts.	279mm SCT
M. Barbieri	Villafranca di Verona, Italy	279mm SCT
T. Barry	Broken Hill, Australia	406mm refl.
D. Basey	Brundall, Norfolk	358mm refl.
M. Bianchi **V**	Milan, Italy	125mm OG
N. D. Biver **V**	Paris, France	407mm refl.
D. Boddington	Swallowfield, Berks.	254mm SCT
R. Bosman	Enschede, Netherlands	355mm SCT
J. Boudreau	Saugus, MA, USA	368mm DK
S. Buda	Melbourne, Australia	405mm DK Cass.
R. Bullen	Forest of Dean, Gloucs.	203mm & 279mm SCT
F. & G. Carvalho	Ribeirão Preto, Brazil	406mm refl.
A. Casely	Sydney, Australia	355mm SCT
P. Casquinha	Palmela, Portugal	355mm SCT
E. & G. Chappel	Cibolo, TX, USA	203mm SCT
A. Cidadão	Carcavelos and Lisbon, Portugal	355mm SCT
A. Clitherow	Fife, Scotland	250mm refl.
M. Collins	Palmerston North, New Zealand	203mm SCT
E. Colombo **V**	Gambarana, Italy	150mm refl.
E. Crandall **V**	Lewisville, NC, USA	254mm refl.
M. Delcroix	Tournefeuille, France	320mm refl.
D. Dierick	Lochristi, Belgium	175mm OG
	Ardennes, Belgium	250mm DK Cass.
C. J. Dole	Newbury, Berks.	180mm MKT
P. Edwards	Horsham, W. Sussex	355mm SCT
H. Einaga	Kasai, Hyogo, Japan	300mm refl.
B. Ellena **V**	Turin, Italy	508mm refl.
C. Fattinnanzi	Montecassiano, Italy	360mm refl.
W. D. Flanagan	Houston, TX, USA	355mm SCT
C. Foster	Centurion, S. Africa	355mm SCT
M. Foulkes	Henlow, Beds.	279mm SCT
S. Gale **V**	Landing, NJ, USA	310mm refl.
D. Gasparri	Perugia, Italy	250mm refl.
M. Giuntoli **V**	Montecatini Terme, Italy	100mm & 150mm OGs
C. Go	Cebu, Philippines	355mm SCT
P. Gorczynski	Oxford, CT, USA	180mm MKT & 355mm SCT
E. Grafton	Houston, TX, USA	355mm SCT
D. L. Graham **V**	Barton, Richmond, N. Yorks.	230mm MKT
D. Gray **V**	Kirk Merrington, Co. Durham	415mm DK Cass.
M. Green **V**	Rhyl, North Wales	203mm SCT
L. Gulliver	Perth, Australia	355mm SCT
N. J. Haigh	Southampton	305mm refl.
T. V. Haymes	Steeple Aston, Oxon.	279mm SCT
A. W. Heath **V**	Long Eaton, Notts.	203mm SCT
R. Heffner	Aichi, Japan	279mm SCT
N. D. Hewitt	Northampton	235mm SCT
R. A. Hillebrecht	Bad Gandersheim, Germany	355mm SCT
R. Hill	Tucson, AZ, USA	152mm SCT
D. A. Holt **V**	Chipping, Herts.	505mm refl.
M. Hood	Kathleen, GA, USA	200mm OG & 355mm SCT
C. J. Hooker	Didcot, Oxon.	203mm MKT
K. C. Howlett	Cwmbran, Gwent	235mm SCT
S. Ito	Kasugai City, Aichi, Japan	250mm refl.
W. Jaeschke	West Chester, PA, USA	355mm SCT
N. D. James	Chelmsford	279mm SCT

Table continuation and explanatory notes on p.162

the dark spot *Caralis Fons* (the floor of *Newton* crater) was very prominent, as it has been for years, attached to the S*f.* (*f.* = following) end of *Mare Sirenum* by a prominent halftone streak. (*Caralis Fons* was not recorded prior to 1926, and has now been visible for many years.)

The Martian atmosphere

Dust storms

Introduction

In a recent paper, Shirley, McKim *et al.* (2020) used dynamical considerations to predict whether global storms might occur during 2020 and at the following three oppositions.[22] Our prediction that there would be no global storm in 2020 proved to be correct. At the time of submission of the present paper, the other predictions remain to be tested.

In the following, we review the smaller events followed by two large regional storms.

Local & small regional storms, 2020 January–October

Some of the smaller events of 2020 are collected in Figure 6.

On 2020 Jan 26–29 (*Ls* = 141–143°), Foster imaged dust in *Cebrenia–Elysium*, which appeared strongly yellowish compared to the evening orographic cloud at *Olympus Mons*, and brighter in red and infrared than in blue light. On Jan 23, *Elysium* had seemed to show only orographic cloud, but there are no other useful observations. On Feb 21 (*Ls* = 154°), he found bright dust over W. *Deucalionis Regio – Thymiamata / Aram – Margaritifer Sinus* (Figure 6A). Invisible on Feb 17, the time course of this local dust could not be followed, but by Feb 26 fallout had again altered the albedo configuration at N. *Margaritifer Sinus* (see also under ‘Region II’ on the previous page, and Figure 5).

In March, there was a brief local event in southern *Zephyria*.[11] Foster on Mar 8 (*Ls* = 163°) imaged three separate small yellowish dust clouds, the activity lasting till Mar 10, as illustrated in Figure 6B. Significantly, activity at this rarely active site had repeated at the same value of *Ls* as in 2018 April.[21]

From Mar 17–29 there was local activity in the south of *Hellas*. A tongue of S. polar hood (SPH) also protruded into the basin, as it had done at this epoch in 2018. MacNeill’s Mar 20 image appears in Figure 6C. On Mar 23, a tongue of SPH stretched north to the *Argyre* basin, and on Mar 25 Foster found *Argyre* much brighter and strongly yellower than before: this marked another short-lived local dust event, which had already faded slightly the following day.

The largest event was a regional storm during Apr 10~16 (*Ls* ~181–184°; Figure 6D). Nothing was visible in Maxson’s or Peach’s images on Apr 8, but on Apr 10, Maxson recorded a large, bright cloud over SE *Margaritifer Sinus* / E. *Mare Erythraeum*. The time course of this event was not completely followed by us but was observed by the cameras of the *Mars Reconnaissance Orbiter* (MRO). On Apr 11–12, dust was observed by Casely, Lonsdale and MacNeill south and east of *Aurorae Sinus*, running along central and E. *Valles Marineris*, affecting *Mare Erythraeum*,

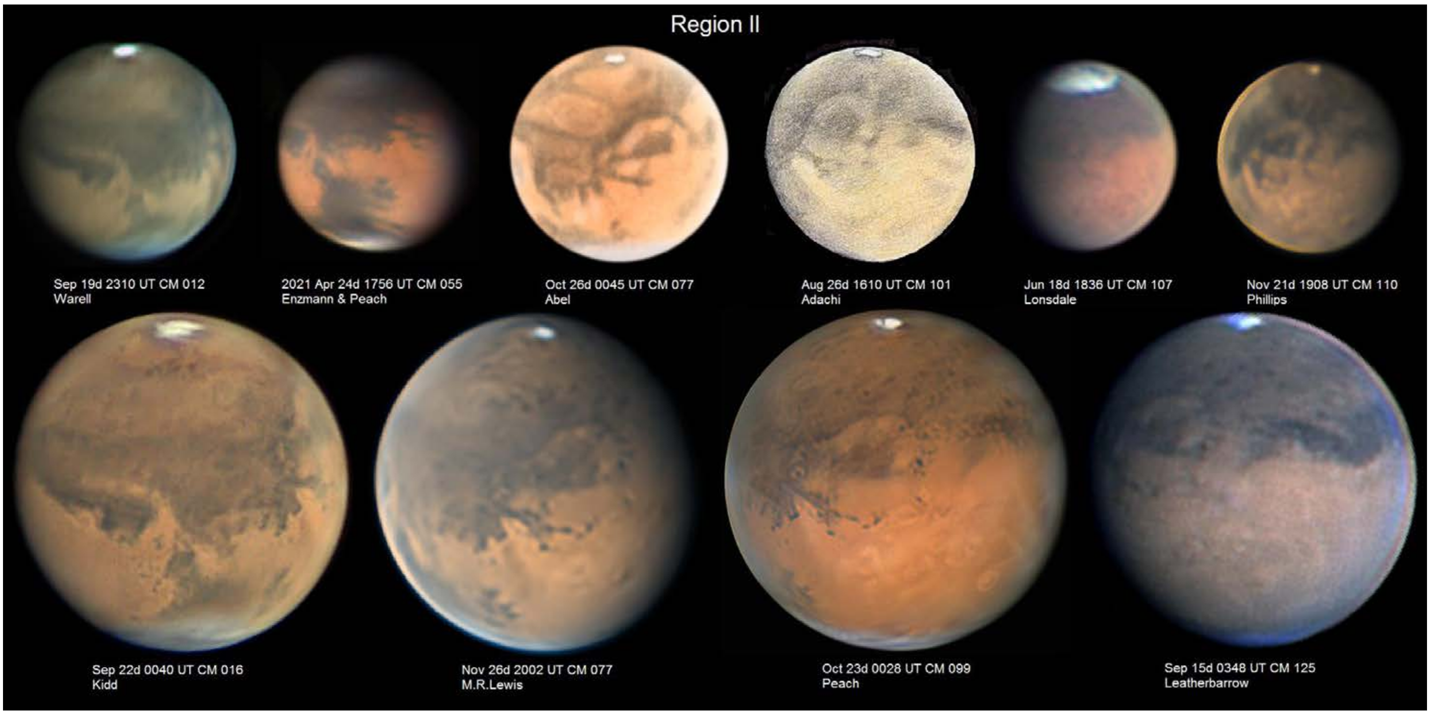

Figure 3. ***Region II.*** Images and drawings in 2020 (except where stated) by P. G. Abel (305mm refl., ×300), M. Adachi (355mm refl., ×589), E. Enzmann & D. A. Peach (1m RCT, Canon 5D Mark 4 camera), A. S. Kidd (ASI 462MC camera), W. J. Leatherbarrow (ASI 290MM), M. R. Lewis (ASI 174MM), W. M. Lonsdale (ASI 290MM), D. A. Peach (355mm SCT and ASI 290MM), M. Phillips (ASI 290MC) and J. Warell (527mm refl., ASI 462MC).

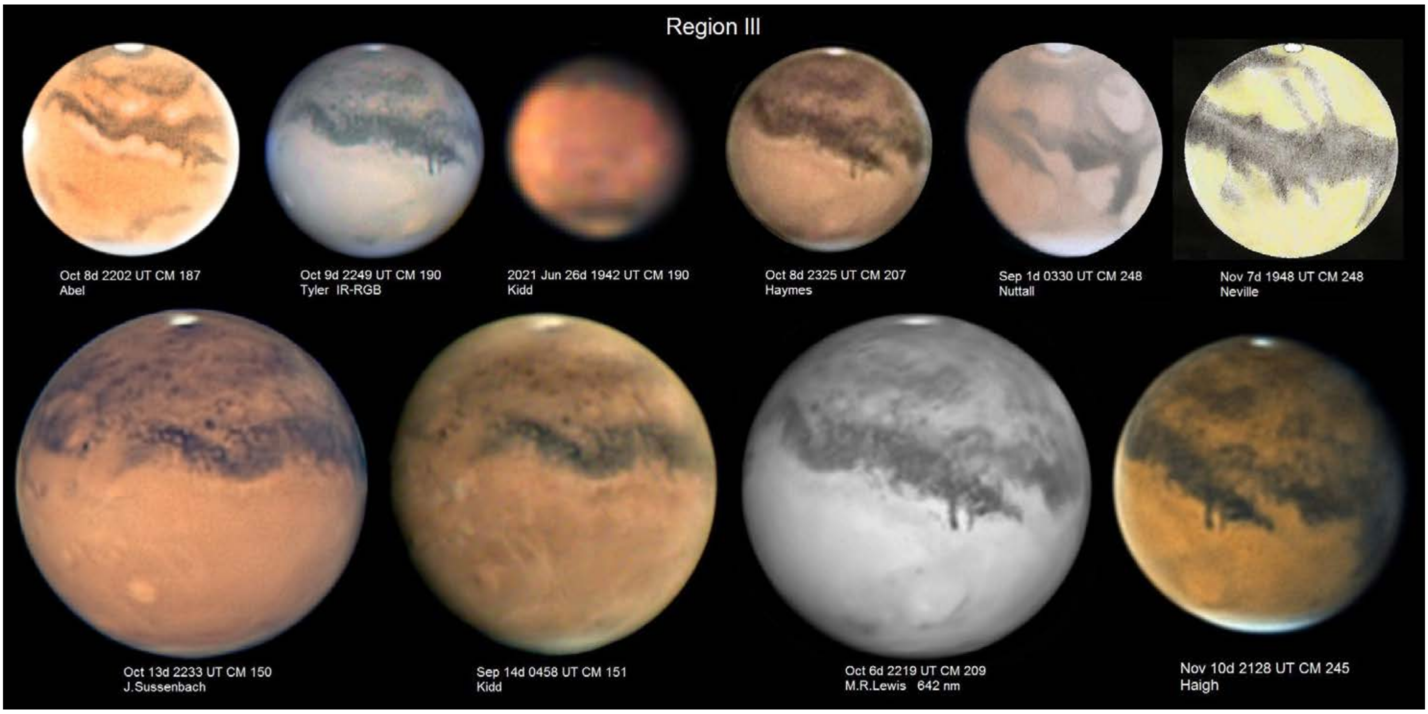

Figure 4. ***Region III.*** Images (RGB except where stated) and drawings in 2020 (except where stated) by P. G. Abel (305mm refl., ×188), N. J. Haigh (ASI 290MM camera), T. V. Haymes (DFK 21AU04), A. S. Kidd (ASI 462MC), M. R. Lewis (ASI 174MM), C. Nuttall (×410), D. B. V. Tyler (ASI 290MM), P. U. Neville (×214) and J. Sussenbach (ASI 462MC).

and substantially penetrating into *Chryse*, crossing the equator. The E. limit was at *Margaritifer Sinus*, whose N. end was briefly effaced. Go showed the event to be fading on Apr 16. MacNeill and Wesley on Apr 17 showed no trace of active dust, but the shape of N. *Margaritifer* had reverted to its post-global-storm aspect (see under 'Region II', p.159, and Figure 6D).

A small dust cloud existed in N. *Chryse* during May 21~23, which did not expand. Arakawa's and Kumamori's images showed it most prominently on May 23.

MacNeill on May 27 observed a small, orange-yellow curved streak of dust near the south pole. Observation of this difficult feature (limited to high-resolution images in fine seeing) was

Table 2. Observers of Mars, 2020 (Cont'd from p.160)

Name	*Location*	*Instrument(s)*
R. W. Johnson	Ewell, Surrey	279mm SCT
M. Justice	Melbourne, Australia	305mm refl.
M. Kardasis	Athens, Greece	355mm SCT
A. S. Kidd	Cottered, Herts.	355mm SCT
D. Kolovos	Athens, Greece	279mm SCT
R. Konnai	Fukushima, Japan	410mm SCT
S. Kowollik	Ludwigsburg, Germany	150mm MKT
T. Kumamori	Osaka, Japan	355mm SCT
S. Kurisu	Mitoyo Kagawa, Japan	355mm SCT
W. J. Leatherbarrow	Sheffield	279mm SCT & 300mm MKT
G. D. Lewis	Bunwell, Norfolk	355mm SCT
M. R. Lewis	St. Albans, Herts.	444mm refl.
R. N. B. Lewis	Rudry, Gwent	254mm SCT
W. M. Lonsdale	Canberra, Australia	279 mm SCT
P. Lyon **V**	Birmingham	203mm SCT
T. McCague **V**	Mesa, AZ, USA	410mm refl.
D. McCracken	Skellingthorpe, Lincs.	203mm SCT
R. J. McKim **V**	Upper Benefield, Northants.	75mm OG, 140mm MKT & 410mm DK Cass.
N. MacNeill	Wattle Flat, NSW, Australia	355mm SCT
S. Macsymowicz **V**	Ecquevilly, France	152mm OG & 235mm Cass. (*etc.*)
P. W. Maxson	Surprise, AZ, USA	250mm DK Cass.
K. J. Medway **V**	Southampton	102mm OG & 200mm refl.
F. J. Melillo	Holtsville, NY, USA	254mm SCT
J. Melka	Chesterfield, MO, USA	457mm refl.
P. Miles	Rubyvale, Queensland, Australia	508mm refl.
D. P. Milika & P. Nicholas	Adelaide, Australia	355mm SCT
T. Mishina	Yokohama, Japan	200mm refl.
E. Morales	Aguadilla, Puerto Rico	310mm SCT
Y. Morita	Hiroshima, Japan	355mm SCT
L. Morrone	Agerola, Italy	355mm SCT
S. Neveu & G. Dawidowicz	Juvisy Obsy., Paris, France	216mm refl. & 248mm OG
P. U. Neville **V**	Maidenhead, Berks.	127mm MKT
D. Niechoy **V**	Göttingen, Germany	203mm SCT
C. Nuttall **V**	York	300mm refl.
T. Olivetti	Bangkok, Thailand	505mm DK Cass.
R. Osborne	Chifley, Canberra, Australia	203mm SCT
A. Pace	Malta	355mm SCT
D. A. Peach	Chilescope Observatory, Andes Mtns., Chile	1m RCT
	Selsey, W. Sussex	250mm DK Cass. & 355mm SCT
& E. Enzmann	La Palma, Spain	760mm Cass.
	Munich, Germany	1m RCT
C. E. Pellier	Paris, France	305mm refl.
	Saint-Véran Obsy., Hautes-Alpes, France	620mm Cass.
M. Phillips	Edinburgh	250mm refl.
J-J. Poupeau	Pecqueuse, France	350mm & 410mm Cass.
A. Pozharov **V**	Stavropol, Russian Federation	500mm refl.
A. R. Pratt	Leeds	279mm SCT
M. Radice	Salisbury, Wilts.	279mm SCT
M. R. Ratcliffe	Wichita, KS, USA	355mm SCT
M. A. Rodriguez	Seville, Spain	279mm SCT
F. Scopelliti	Volta Mantovana, Italy	600mm refl.
R. Severn	Nottingham	279mm SCT
I. D. Sharp	Ham, W. Sussex	279mm SCT
W. P. Sheehan & S. Burcher	Lowell Obsy., Flagstaff, AZ, USA	600mm OG
P. C. Sherrod	Petit Jean Mtn., AK, USA	410mm SCT
I. S. Smith **V**	Wolverhampton, W. Midlands	128mm OG
A. Snook **V**	Dover	130mm OG
D. Storey	Douglas, Isle of Man	355mm SCT
D. Strange	Salcombe Regis, Devon	235mm SCT
R. & S. Stuart	Rhayader, Powys	250mm refl.
E. Sussenbach	Willemstad, Curaçao, Dutch Caribbean	279mm SCT
J. Sussenbach	Houten, Netherlands	355mm SCT
R. Tatum	Henrico, VA, USA	305mm SCT
P. Tickner	Lower Earley, Berks.	355mm SCT
A. B. Thomas	Warrington, Cheshire	200mm refl.
C. Towell	Bristol	220mm refl.
R. H. Tremblay	St-Augustin de Desmaures QC, Canada	140mm OG
D. B. V. Tyler	Flackwell Heath, Bucks.	355mm SCT
M. P. Valimberti	Melbourne, Australia	305mm refl.
V. della Vecchia	Aversa, Italy	203mm SCT
K. Venables **V**	Camberley, Surrey	102mm OG & 457mm refl.
V. Verbitskiy	Novosibirsk, Russian Federation	355mm DK Cass.
D. Vidican	Bacau, Romania	152mm refl.
A. Vilchez	Grenada, Spain	180mm DK Cass. & 279mm SCT
G. Walker	Macon, GA, USA	254mm OG & 300mm DK Cass.
I. L. Walton	Cranbrook, Kent	570mm refl.
J. Warell*	Skivarp, Sweden	527mm refl.
A. Wesley	Rubyvale, Queensland, Australia	415mm refl.
T. E. Williamson	Albuquerque, NM, USA	315mm refl.
J. Willinghan	Elkridge, Maryland, USA	305mm SCT
P. Wirtanen* **V**	Pähkinärinne, Vantaa, Finland	127mm MKT
K. Yunoki	Osaka, Japan	355mm SCT

Abbreviations: OG = object glass (refractor); refl. = reflector; Cass. = Cassegrain; DK = Dall–Kirkham; MKT = Maksutov–Cassegrain; RCT = Ritchey–Chrétien and SCT = Schmidt–Cassegrain (Telescope).

All observers sent images except those marked **V** (for visual observations *only*).

*Warell also sent a report of the Solar System Section, Svensk Amatör Astronomisk Förening (Swedish Amateur Astronomical Society), from *Telescopium*, **21**(1), 5–11 (2020), and Wirtanen an analysis of Finnish amateur Mars observations in *Zenit* (2021).

repeated by Foster, MacNeill and Kumamori till Jun 14. Again, during Jun 20–30, the sharpest images showed a tiny static (but obviously yellowish-orange) patch of dust activity very close to the areographic south pole. Such activity was also seen in 2003.[23]

As the south polar cap (SPC) was recessing at maximum velocity, several local dust clouds were spotted at its N. edge, some lasting for several days. It is important to avoid confusion with those parts of the cap that seasonally detach from it, for example *Thyles Mons*. We recorded several such features during 2020 Jul 4 – Nov 11, especially during August–September, and only a few are cited here. These initially changeable streaks give rise to static fallout, which are then rapidly dispersed. A small dust cloud west of the large regional storm of June–July was captured by Peach on Jul 3 (Figure 6E), when the cap edge at that longitude was yellowed by dust. MacNeill saw complex activity at the cap edge on Jul 31 – Aug 5 (Figure 6E). Pellier on Aug 5 (see the second interim report,[12] Figure 2) & 9 showed a yellowish N*p.*–S*f.*-trending streak, well separated from the SPC N. edge, under a central-meridian (CM) longitude of 114–159° and north of the outlier *Thyles Mons*. By Aug 13 it had greatly faded. The same streak was imaged (for example) by J. Sussenbach on Aug 2 (Figure 6E), Arditti on Aug 7 (Figure 6E), and Peach on Aug 7–10.

In their best September–October images, Carvalho, Kolovos, Kumamori, Peach (Figure 6E), Scopelliti (Figure 6E), and Wesley (Figure 6E) all caught a complex pattern of streaks around the much-shrunken SPC, over a wide range of longitude. The

Director saw such a streak N*f.* the cap under CM = 073° on Sep 12, and under CM = 348° on Sep 20. This phenomenon seems to have consisted of water-ice 'cascades' from the subliming cap, mixed with dust stirred by the off-cap winds. Cascades are also seen in MacNeill's images of Jul 31 – Aug 5 (Figure 6E): on the latter date an obvious dusty area lay to the west of the cascades emanating from the SPC.

Several terminator projections were seen, when dust was not bright enough to be obvious near the CM. Kumamori's images (typically derotated for ~20 minutes) on Aug 16 (CM = 215–235°), 18 (most noticeable around CM = 210°; Figure 6E), 19 (CM = 203°, much reduced by 217°) & 20 (CM = 185°, increasing at 200°) recorded a dusty projection of wide latitudinal extent. Konnai on Aug 24 (CM = 195°) saw the same feature as slightly yellowish.

Finally, an obvious dust front crossing *Mare Acidalium* diagonally (N*p.* to S*f.*) was imaged by Pellier on Oct 30. This may have been significant in relation to the initiation of the large November regional storm (see below).

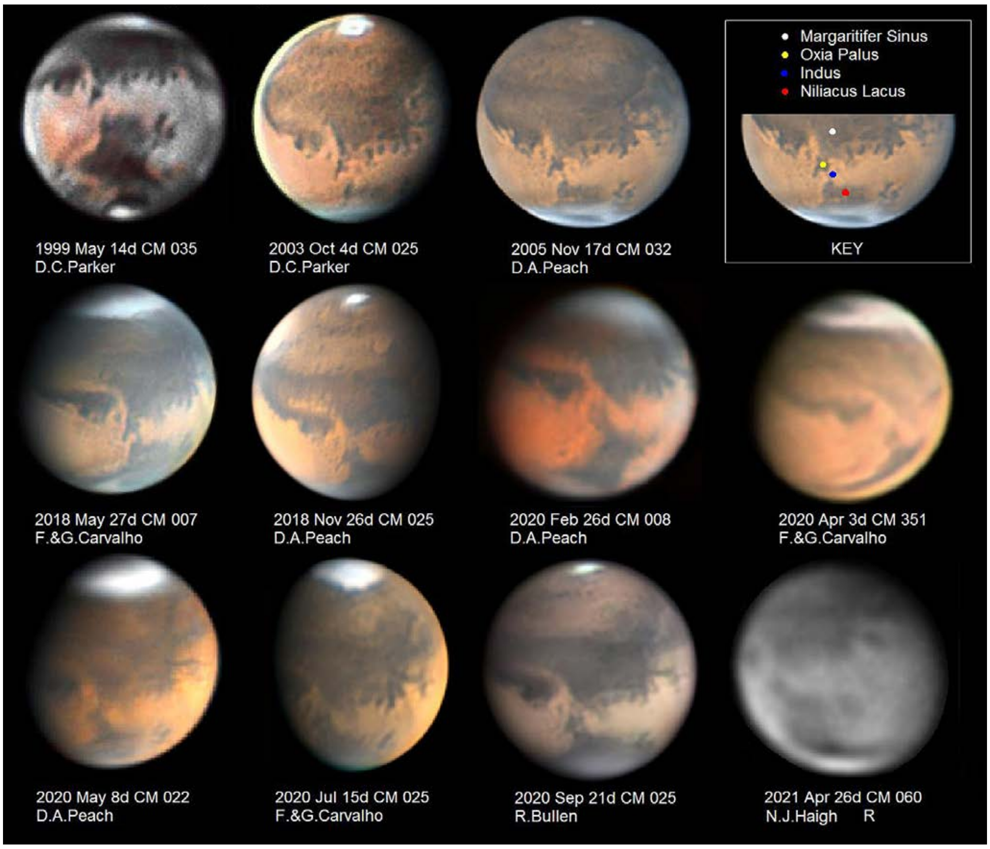

Figure 5. Images showing albedo changes at *Margaritifer Sinus*, *Oxia Palus* and *Indus*, 1999–2021.

Large regional storm, 2020 June–July

Activity had commenced by Jun 22 (*Ls* = 225°) to the north and west of *Aurorae Sinus*, according to images by Einaga. Dust also lay across W. *Mare Erythraeum*, suggesting that activity had probably commenced the previous day. (Nothing was visible on Jun 20.) The event was soon confirmed by other Australasian observers, and an alert from the Director was posted on the BAA Forum. Lasting more than a fortnight, this ultimately large regional storm (Figure 7) stretched from *Hellespontus* to W. *Thaumasia*.

By Jun 23, dust was affecting central *Valles Marineris* and S. *Chryse* to S. *Xanthe*, while the initial cloud north of *Aurorae Sinus* (containing four or more brighter nuclei) had extended to *Chryse Planitia* in the north and had cut *Ganges* in the south. *Margaritifer Sinus* was faint by Jun 25, by when (according to the most detailed images, by Milika & Nicholas) dust had invaded *Argyre*, and a thin stream crossed E. *Thaumasia*, to cut across *Solis Lacus* and to end east of *Gallinaria Silva*. (A little fallout would linger a few days here.) On Jun 27, *Sinus Meridiani* remained dark compared to *Margaritifer* and the *Chryse–Xanthe* dust was markedly fading, but *Noachis* was dusty. Next day, dust activity continued in *Valles Marineris* and to the south, with a bright new dust core at the W. end of *Deucalionis Regio*, while *Margaritifer* was already faintly reappearing. On Jun 29, Casely's images showed dust was still invading *Noachis*, but there was clearly a general decline, and by Jul 1 images such as Kumamori's in Figure 7 showed that the evolution of the event was virtually complete: a temporary low-albedo anomaly appeared in W. *Noachis*, while *Hellespontus* had been greatly broadened. *Noachis* was rather light, and *Argyre* bright and yellow due to fallout.

Contrast in the affected region remained low visually for some days. Even on Jul 11–12, Abel (Figure 7) and McKim found low contrast around *Noachis* and *Argyre*, the latter still bright due to fallout, with the limb brightening being fainter, more diffuse and yellowish than normal. *Margaritifer Sinus* was still rather faint. The effect of the storm upon *Pandorae Fretum* and *Deucalionis Regio* was described under 'Region I'.

To the great relief of many observers, the Martian skies remained clear for a long period around opposition.

Large regional storm, 2020 November–December

A large regional storm was observed during Nov 11~27. It eventually stretched from *Ausonia* in the east to *Daedalia* in the west. (See Figures 8 & 9.) Covering mostly the southern hemisphere, this event did not affect the N. polar hood, and the colour of most northern deserts was unchanged.

A few days after Pellier had imaged a dust front crossing *Mare Acidalium* on Oct 30 (see earlier), small local dust clouds were observed precisely over *Juventae Fons* and around *Nilokeras* on Nov 5. This activity lasted only one day, but a resurgence occurred a few days later. On Nov 11 (*Ls* = 313°), a very small dust cloud over *Chryse Planitia* appeared upon images by Kumamori and Yunoki from 11:23 UT, but had not been discerned at 09:34 UT. Next day, it was much more conspicuous to Adachi and Chappel, occupying S. *Chryse* and the N. part of the *Valles Marineris* canyon system. On this date, half a dozen or more tiny new dust cores were resolved. The Director posted a website alert. On Nov 13, the dust clouds had expanded along *Valles Marineris* and showed no obvious change over six hours' observation. The seasonal date, location and initial shape all resembled the start of the large regional storm of 2005 October. On Nov 14, dust had expanded to the west across *Ganges*, *Juventae Fons* and into *Valles Marineris*, marking out the full extent of the complex canyon system, and southward over *Mare Erythraeum*.

On Nov 15, the western end of the event was observable from the UK in the early evening, with a number of bright dust clouds turning the evening limb yellow from *Chryse* to S. *Mare Erythraeum* as viewed by the Director. Images revealed new cores in S. *Chryse* and east of *Solis Lacus*, and there was further expansion over *Mare Erythraeum* and to E. *Argyre*. The *Valles Marineris* dust had become fainter in the short canyon north of and parallel to the main one just east of *Aurorae Sinus*, compared with the previous day, though the main section was undiminished in brightness. Next day, it brightened again, and dust began to expand over *Bosporos Gemmatus* into the desert around *Solis Lacus*, and partly cut across the latter feature. Active regions remained at *Chryse*, *Juventae Fons* and *Ganges*. On Nov 16 & 17, another E–W-oriented front of dust was moving south across *Mare Acidalium*.

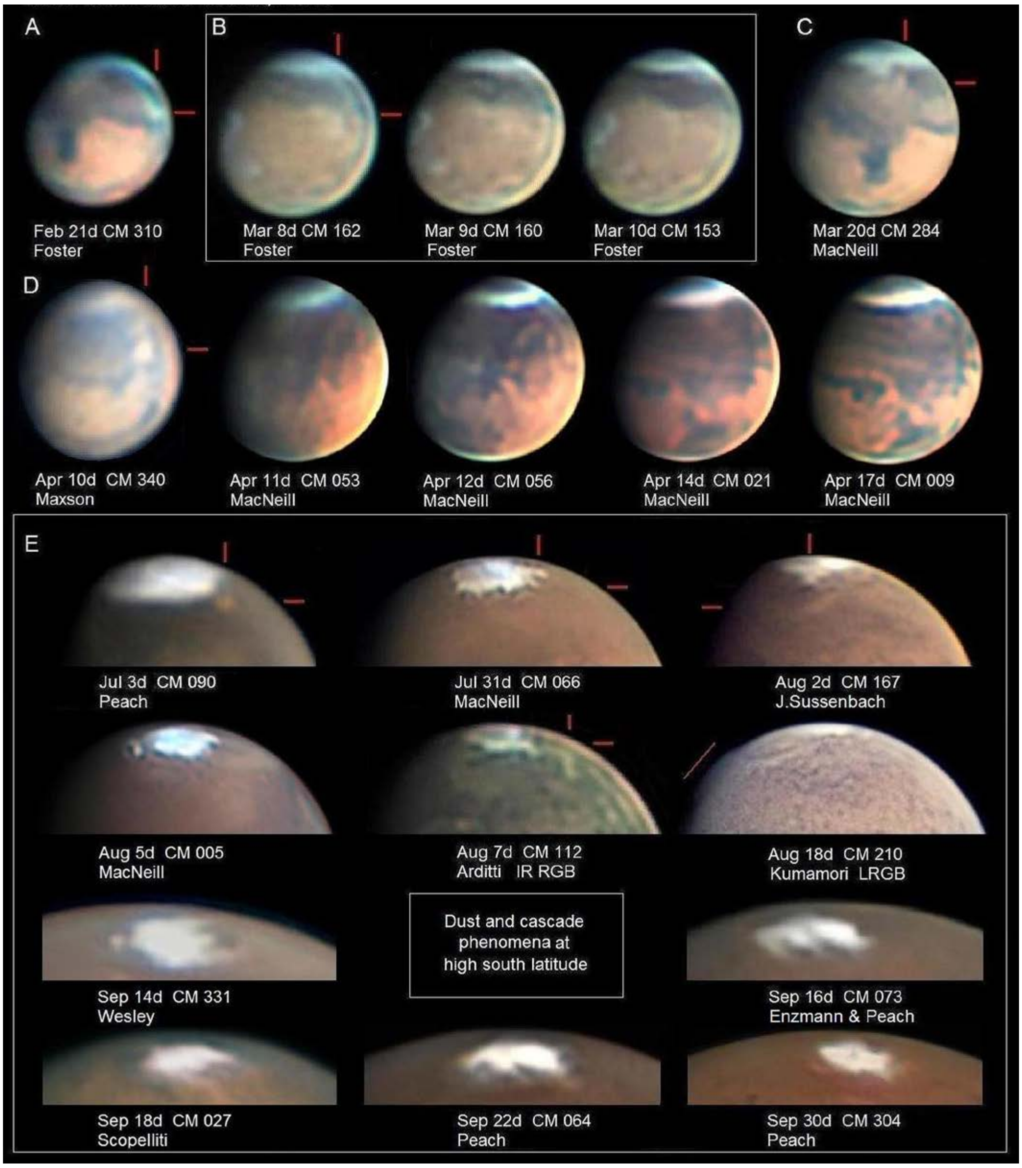

Figure 6. Small-scale dust storms during 2020. **(A)** Local dust storm at W. *Deucalionis Regio – Margaritifer Sinus*, 2020 February; **(B)** local dust storm over S. *Zephyria* and environs, 2020 March; **(C)** local dust storm in W. *Hellas*, 2020 March; **(D)** small regional storm over *Valles Marineris – Margaritifer Sinus* and S. *Chryse*, 2020 April; **(E)** dust and 'cascade' phenomena at high south latitude, 2020 July–September (each row of part (E) is approximately to scale).

On Nov 17, dust had spread over western *Noachis* and over *Argyre*; further dust-raising in the form of several small cores started over *Sinus Meridiani*; bright cores were seen over and south-west of *Solis Lacus*; *Valles Marineris* remained bright and dusty, and further north there was still activity over *Chryse*. On Nov 18, an irregular belt of creamy-yellow dust (with brighter condensations) stretched diagonally from *Argyre* across *Bosporos / Phrixi Regio* as far west as *Aonius Sinus*, obscuring part of central and S. *Solis Lacus*. Dust headed east at high latitude, as far as S. *Hellespontus*, though there had been no eastward progression from N. *Noachis*. Activity continued within *Valles Marineris*, and *Margartifer Sinus* had become affected, but dust over *Sinus Meridiani* had for now dispersed. The W. end of the storm did not develop further, and instead it gradually faded over several days, as did the dust cloud over *Solis Lacus*. On Nov 19, the bright core at *Aram* had become very prominent; next day it affected *Sinus Meridiani*, and another complex area of bright cores appeared around E. *Deucalionis Regio*, while the *Marineris* dust seemed less bright. Dust continued to affect SE *Noachis* (the south-west being unaffected) as far as *Hellespontus*, and these areas now could be seen near the evening limb from the UK.

Some anomalous darkening at high latitude near the SPC, adjacent to the *Noachis* cloud, was observed on Nov 21. (The encircling storm of 1956 – and large regional events in 1988 and 2003 – provide other good examples of this effect.) A similar phenomenon was seen at the S. edge of the *Deucalionis* cloud. The *Deucalionis* and *Aram* cores remained bright, and dust cut across *Sinus Sabaeus* to form a core at *Edom*, which however faded next day. The W. end of the storm, together with the dust belt across *Bosporos*, was fading further. On Nov 22, the *Aram* core was fading too, with the individual *Deucalionis* cores now merged. The entire W. side of the event was fading, with contrasts around *Solis Lacus*, *Aurorae Sinus* and western *Erythraeum* nearly back to normal, though the latter looked mottled by complex dust features to the Director. *Argyre* was bright yellow with fallout. But dust was still advancing east to cross *Yaonis Regio*.

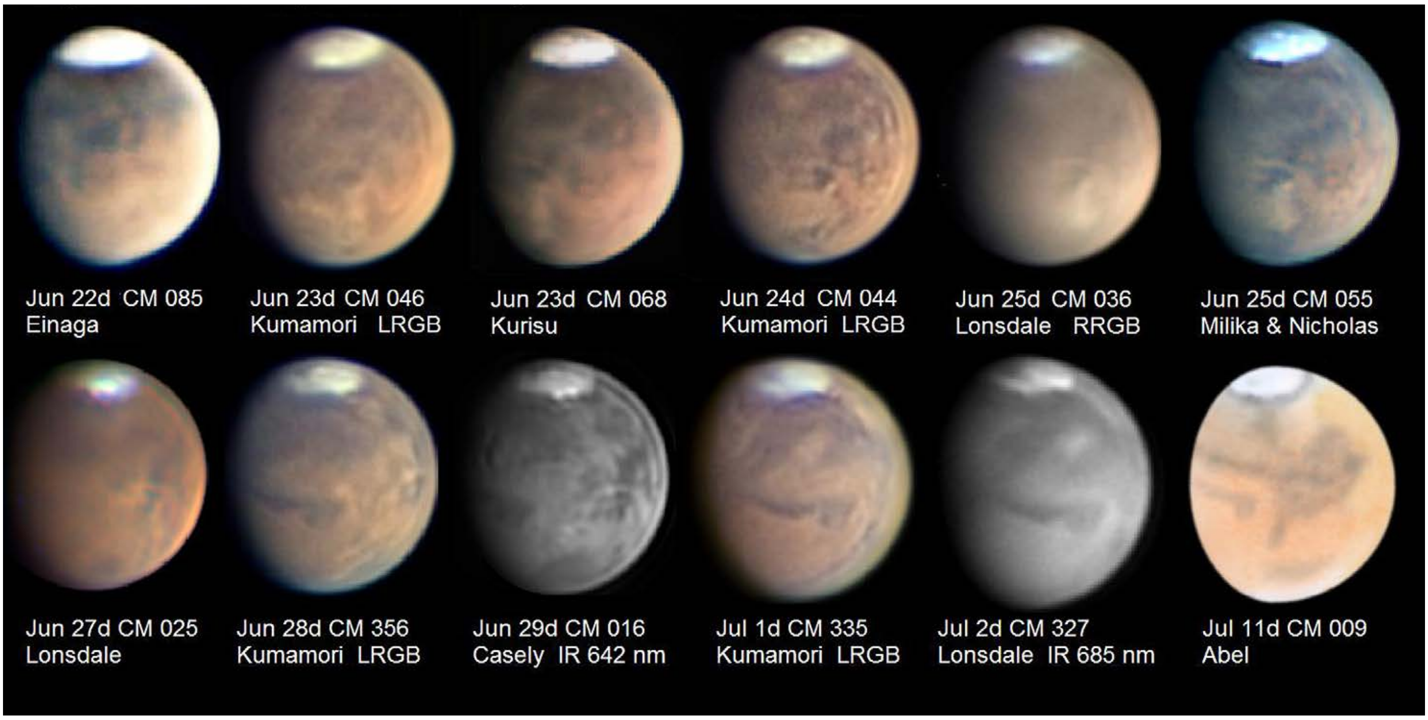

Figure 7. Images and a drawing (Abel, 203mm refl., ×200) of the large regional dust storm of 2020 June–July.

On Nov 23, dust entered the NW and W. parts of *Hellas*, this being the only very bright area remaining. It did not travel further south than *Zea Lacus* and after a few days of continued activity, with some dust reaching NE *Hellas* and propagating eastward as far as N. *Ausonia* by Nov 25, as well as some patchy fallout across S. *Iapigia*, the event ended. The Director found the evening limb still very yellow on the latter date, when it coincided with the longitudes affected by the dust, and the static nature of the light yellow *Valles Marineris* suggested fallout. By Nov 26, the *Hellas* dust too was subsiding; it and *Ausonia* no longer showed daily changes. Contrast seemed normal to the Director by Nov 30, but there was some transport of dust over the SPC, for it had faded between Nov 26 & 30. On Dec 1, contrasts remained a little low, but all features were recognisable.

At its maximum, high-altitude dust caused obvious projections beyond the southern terminator. One of the clearest examples was recorded by Wesley on Nov 20, under CM = 353°, from which the writer measured its height using the standard formulae to be 16km.[24] It was located near –57°, 080°. This, and a similar feature from Nov 18, are indicated in Figure 8. Other sightings fell between Nov 13 & 21. It was noticeable that this regional event and the specific terminator projections were also bright in blue light, suggesting a significant water ice component – derived from the recently recessed SPC. [*Added at proof:* Lilensten J., Dauvergne J. L., *et al*., in *Astron. Astrophys*., **661**, A127 (2022) [doi.org/10.1051/0004-6361/202141735] found that a faint dusty arc (also visible in blue light), detached from the terminator on Nov 17 over latitudes ~0 to –50°, projected beyond it to a maximum height of around 92km.]

Kumamori prepared map projections for many dates during Nov 11–28, and Kardasis one for Nov 16, from which we could deduce representative velocities, all of which were quite typical. Between Nov 12 & 13, dust north of *Aurorae Sinus* propagated west along *Valles Marineris* at 56km h^{-1}, which is considerably faster than it had expanded there at the start of the 2018 global storm. In the same interval, the expansion to the east was much lower, at 12km h^{-1}, while southward across *Mare Eythraeum* (measured at longitude 45°) it was 25km h^{-1}. At the same longitude, between Nov 13 & 14, dust continued to propagate south across *Erythraeum* at 28km h^{-1}. From Nov 15–16, dust travelled west from SW *Erythraeum* across *Bosporos* to *Solis Lacus* at 45km h^{-1}. From Nov 19–21, the E. part of the new core at *Aram* – W. *Deucalionis Regio* moved eastward at 57km h^{-1}, showing that the expansion of the new core in this direction was more rapid than that of the original.

In Appendix I, we summarise the mathematics needed to derive velocities.

Further dust activity, 2021 January onwards

On 2021 Jan 3 (Ls = 342°), Haigh showed local dust stretching from *Chryse Planitia* and *Nilokeras* across *Mare Acidalium* at the latitude of *Achillis Pons*. The only suggestion of it upon his image the following day was a possibly dusty area over and just east of *Indus*. The Director had good seeing on Jan 5 and saw no trace of it visually.

General discussion

As we have seen, there was no encircling or global storm in 2020, but plenty of smaller-scale activity. A tiny dust cloud was seen near the south pole in June, several events occurred at the edge of the recessing cap, and there were several regional events whose seasonal occurrence was typical. The rarely active S. *Zephryria* site that had been active in 2018 again produced a local event in 2020.

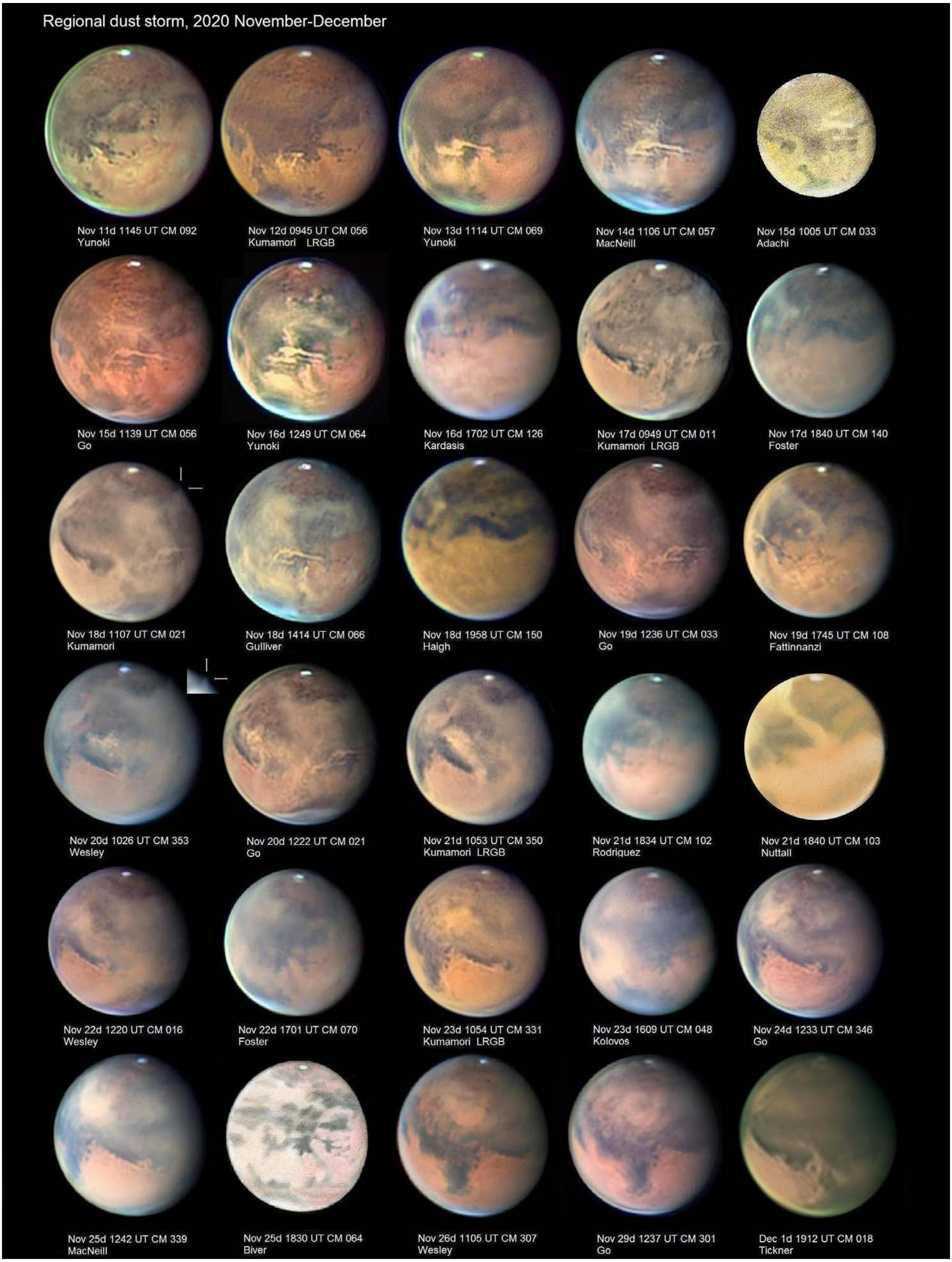

Figure 8. Images and drawings (Adachi, ×400; Biver, ×700; Nuttall, ×410) of the large regional dust storm of 2020 November–December.

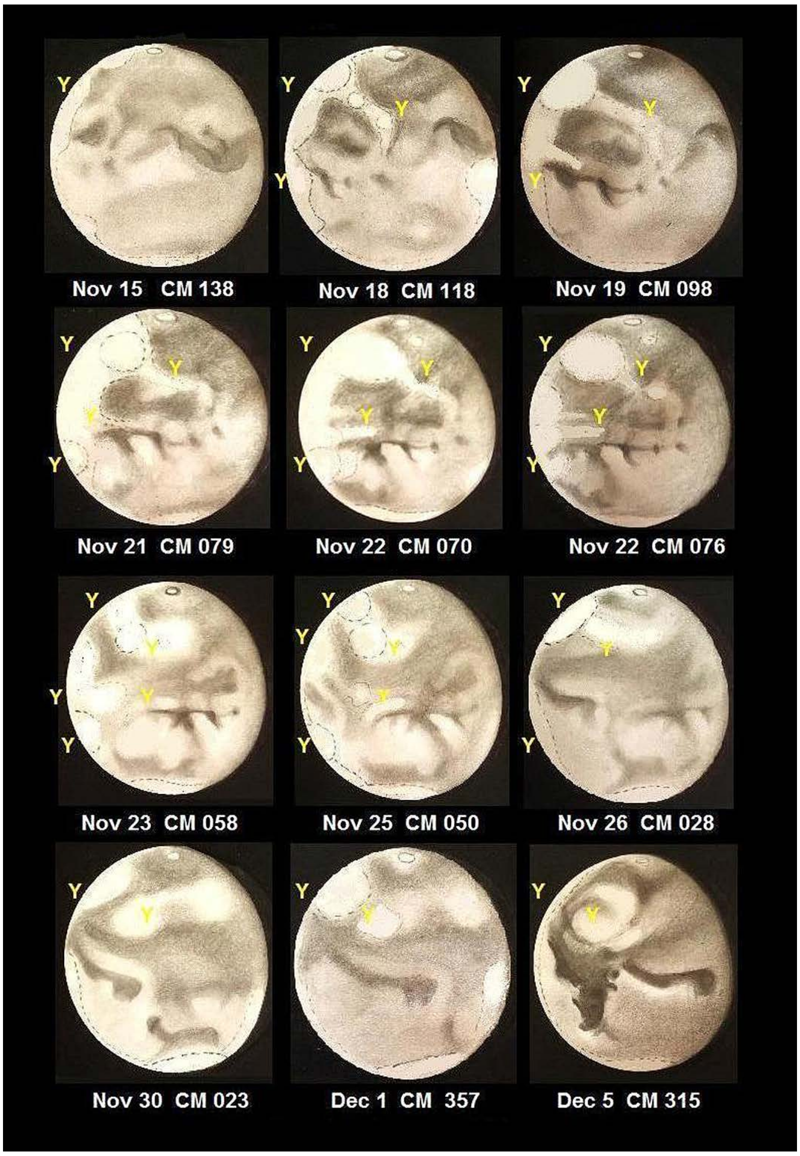

Figure 9. Drawings by R. J. McKim (410mm DK Cass., ×265, ×331, white light/W23A orange filter) showing the large regional dust storm of 2020 November–December.

Two events attained large regional status, both of which developed in the same manner and to roughly the same extent. The currently favoured emergence source of S. *Chryse–Xanthe* at the northern boundary of *Valles Marineris* again marked their commencement; they spread south-east towards *Hellas* and westward over *Thaumasia.* The writer has noticed how this emergence source has gradually come to dominate the scene in recent Martian years. In Appendix II and Table 3 we give a post-1993 catalogue of large regional telescopic storms, comparing them with the previously more common type that began in NW *Hellas* or nearby, and which propagated west towards *Argyre*.

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13 For details of the NASA helicopter, see McKim R. J., *ibid*., **131**, 137 (2021). (*Erratum*: its weight was just under 2kg, and not as stated.) *Perseverance* was able to successfully extract oxygen from

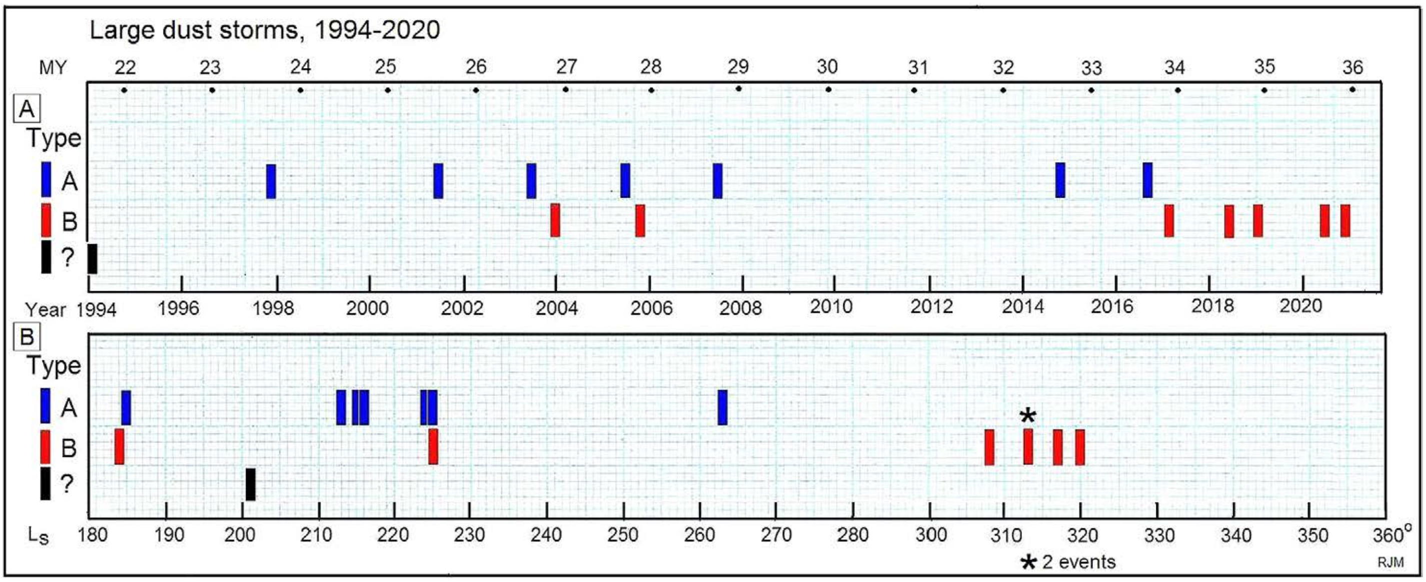

Figure 10. (A) Timeline, in terrestrial and Martian Years (MY). **(B)** *Ls* distribution graph for large regional storms of types A and B (as defined in the text), and encircling or global storms, 1994–2020. *(R. J. McKim)*

the Martian atmosphere using its MOXIE instrument, some details of which appeared the day after the experiment, in a press release dated 2021 Apr 21. Atmospheric carbon dioxide was split into carbon monoxide and oxygen at 800°C, and the two gases separated. This paves the way to sending an 'oxygen converter' to Mars ahead of a crewed mission: something previously encountered only in science fiction. See: **https://www.nasa.gov/press-release/nasa-s-perseverance-mars-rover-extracts-first-oxygen-from-red-planet** (accessed 2021 August)
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Table 3: Large dust storms, MY 21–35

MY	*Initiation date*	*Ls (°) at start*	*Type A or B*	*Regional (R), Encircling (E) or Global (G)*
21	1994 Jan 14*	201	(?)	E (G?)
23	1997 Nov 25	224	A	R
24†				
25	2001 Jun 26	185	A	G
26	2003 Jun 30	213	A	R
26†	2003 Dec 9	313	B	R
27†	2005 Jun 5	225	A	R
27	2005 Oct 17	308	B	R
28	2007 Jun 23	263	A	G
29–32†				
32‡	2014 Oct 17	216	A	R
33†	2016 Sep 2	215	A	R
33	2017 Feb 20§	320	B	R
34	2018 May 30	184	B	G
34	2019 Jan 2	317	B	R
35†	2020 Jun 22	225	B	R
35	2020 Nov 11	313	B	R

* Ground-based CO microwave data showed a large rise in atmospheric temperature at all longitudes (till *Ls* ~260°). Atmospheric temperatures are strongly affected by regional as well as by encircling storms, but its long duration and current professional opinion point to it being encircling. Without latitude data it is impossible to determine whether or not the event was truly global. Shirley, McKim, *et al*. (2020) gave *Ls* = 201° for the start of the event.[22]

† No encircling storm in this MY (BAA and spacecraft)

‡ A number of small regional events were detected by spacecraft and partially recorded by BAA observers, 2015 March–April, from *Ls* = 307°, one of which was clearly of Type B.

§ Two apparently successive regional storms, partially observed by the BAA, were followed by MRO. The first began on 2017 Feb 20 but did not reach 100° in longitude; it was abating in early March when a second event achieved regional status by Mar 5, ultimately meeting our 'large regional' criterion.

Appendix I. Measuring the velocities of Martian clouds

Over very small distances, or along parallels of latitude, plane geometry is adequate for deriving velocities of Martian clouds. When significant changes in latitude occur, or over large distances, one must use spherical trigonometry. Some of our pre-2018 reports contain estimates of velocity, but generally over the same parallel of latitude. As images became more detailed, more precise information could be derived from them. In our 2018 report,[15] we quoted a considerable number of velocities.

Let P represent the aerographic S. pole. Imagine that a dust storm or other cloud has been observed on two dates at locations Q and R respectively. PQ and PR are parts of great circles with a radius equal to that of the planet, and triangle PQR is therefore a spherical triangle whose apex is the S. pole. Angle A is equal to the difference in longitude between Q and R. Let PQ = a, PR = b and QR = c. The sides of the triangle, a, b and c are expressed in degrees. The angular distance a is equal to 90° minus the latitude of point Q (provided they are in the same hemisphere, or to 90° plus latitude if not). Likewise, the angular distance b is equal to 90° minus the latitude of point R. The angular distance a travelled by the dust can then be found from:

$$\cos a = \cos b \cos c + \sin b \sin c \cos A$$

If we prefer to use the latitudes of Q and R directly, denoted b' and c', given that $\cos (90–\alpha) = \sin \alpha$, and *vice versa*, the expression becomes:

$$\cos a = \sin b' \sin c' + \cos b' \cos c' \cos A$$

The derived angular distance a (which like b and c lies upon a great circle of planetary radius r) can be converted into kilometres:

$$\text{distance} = 2 \pi r a/360 \text{ where } r = 3{,}397\text{km}$$

The velocity of the cloud follows directly.

Appendix II. Large dust storms, 1994–2020 (MY 21–35)

All historical data up to and including 1993 have been discussed by the writer.[26]

At the start of the period under review, regional dust storms that began in NW *Hellas* (or occasionally *Noachis*) and spread westward to *Argyre* were relatively common. These the writer calls Type A storms, and they often cause the darkening of *Pandorae Fretum* at the N. edge of *Noachis*. At the present time it has become more common for regional events to commence in S. *Chryse–Xanthe* at the border of *Valles Marineris*, and spread to the south-east (sometimes reaching *Hellas*), south over *Mare Erythraeum* and *Argyre*, and westward over *Thaumasia*, sometimes as far as *Daedalia*. These he calls Type B. Very often a secondary dust core forms at *Aram*. If a Type B event begins in N. *Chryse* or N. *Xanthe* (*Chryse Planitia*) rather than their southern limits, they are of a cross-equatorial nature. H. Wang (2003) stated that the propagation of cross-equatorial storms was only possible in the *Ls* intervals 210–230° and 310–350°.[25] The global storm of 2018 was of the latter type, and the development of further cores enabled it to become encircling, as might also happen with a Type A event.

Table 3 is a list of regional events of both types, excluding those smaller storms whose longitudinal extent was less than ~100°: we exclude events observed only by spacecraft. (There will of course be many regional storms that were observed only from Martian orbit, which, for consistency with our previous study,[26] we do not consider.) These data are plotted by terrestrial date and by *Ls* in Figure 10. The *Ls* distribution differs because the latitudes of the initiation sites of Type A and B storms differ substantially. Despite the temporal limitations imposed by ground-based coverage, with years passing when we could not watch the S. spring or summer in enough continuity or detail, it is striking how the Type B regional events have become much more common than Type A.